ONR ASSESSMENT SERIES

1999 Assessment of the Office of Naval Research's Air and Surface Weapons Technology Program

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1999 Assessment of the Office of Naval Research's Air and Surface Weapons Technology Program

Committee on the Review of ONR's Air and Surface Weaponry Program
Naval Studies Board
Commission on Physical Sciences, Mathematics, and Applications
National Research Council

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Preface

The mission of the Office of Naval Research (ONR) is to maintain a close relationship with the research and development community to support long-range research, foster discovery, nurture future generations of researchers, produce new technologies that meet known naval requirements, and provide innovations in fields relevant to the future Navy and Marine Corps. Accordingly, ONR supports research activities across a broad range of scientific and engineering disciplines. As one means for ensuring that its investments appropriately address naval priorities and requirements and that its programs are of high scientific and technical quality, ONR requires that each of its departments undergo an annual review (with a detailed focus on about one-third of the reviewed department's programs). The Air and Surface Weapons Technology (ASWT) program resides within the Strike Technology Division of the Naval Expeditionary Warfare Science and Technology Department of ONR and accounts for approximately 25 percent of the department's budget.

At the request of ONR, the National Research Council (NRC) established a committee to review and evaluate ONR's ASWT program components in the mission areas of air superiority, precision strike, naval fire support, ship-based defense, and supporting science and technology, including uninhabited combat air vehicles, against criteria such as appropriateness of the investment strategy within the context of naval priorities and requirements, impact on and relevance to naval needs, and scientific and technical quality. In the selection of committee members, expertise was drawn heavily from the following areas: guidance and control, fire control, aeromechanics, solid and air-breathing propulsion, naval gun systems and launchers, and uninhabited combat air vehicles. The Committee on the Review of ONR's Air and Surface Weaponry Program met once, May 26-28, 1999, in Washington, D.C., to both gather information and prepare an initial draft report. The three-day meeting was divided into two parts: the first comprised presentations by and interactions with project managers (and ONR-supported principal investigators) responsible for various program components, and the second was devoted to drafting the committee's findings and recommendations and developing consensus on them.

The resulting report represents the committee's consensus views on the issues posed in the charge.

Acknowledgment of Reviewers

This report has been reviewed by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's (NRC's) Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the authors and the NRC in making the published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The contents of the review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their participation in the review of this report:

Roy R. Buehler, Lockheed Martin,
James W. Dally, University of Maryland,
Earl H. Dowell, Duke University,
L. Raymond Hettche, Applied Research Laboratory, Pennsylvania State University,
Edwin L. Key, Mitre Corporation (retired),
William M. Locke, RADM, USN (retired), and
Jeffrey Wadsworth, Lawrence Livermore National Laboratory.

Although the individuals listed above provided many constructive comments and suggestions, responsibility for the final content of this report rests solely with the authoring committee and the NRC.

Contents

Executive Summary

The Office of Naval Research (ONR) contracted with the National Research Council (NRC) to establish a committee to review ONR's Air and Surface Weapons Technology (ASWT) program. The program review was held on May 26 and 27, 1999. This report is based on the information presented at the review.

The ONR ASWT program resides within the Strike Technology Division of ONR's Naval Expeditionary Warfare Science and Technology Department and accounts for approximately 25 percent of the department's budget. The program comprises the following weaponry mission areas: air superiority, precision strike, naval fire support, and ship-based defense, as well as a supporting science and technology (S&T) 6.1 and 6.2 effort including uninhabited combat air vehicles (UCAVs). Except for the supporting S&T work, the performing organizations were the Naval Air Warfare Center (NAWC) China Lake, and the Naval Surface Warfare Center (NSWC) Dahlgren. Industrial contractors provide support to both the NAWC and the NSWC and, together with academic contractors, perform the work in the supporting S&T area.

In formulating the concerns, conclusions, and recommendations in the specific areas presented, the Committee on the Review of ONR's Air and Surface Weaponry Program used its own judgment based on its expertise in naval operations, systems, and technology. Generally, the committee found that most elements of the ASWT program were coupled to stated future Navy and Marine Corps needs. In each mission area, there were specific opportunities for timely transitioning of technology into naval weapon system development programs which were considered in order that meaningful, exploitable technology development could be ready in time for introduction into these programs. In many cases, knowledge of parallel efforts in other services or agencies was evident. The ASWT program also exhibited cooperation with industry and leveraging of industry independent research and development (IR&D).

For the most part, the work in the program components was focused on the right time frame—far enough into the future without being futuristic. Although specific comments on individual program components are made in Chapter 2 of this report, the committee points out here its finding that the work on enhancements of the extended-range guided missile (ERGM) at NSWC Dahlgren, which could be transferable to a pure missile system, was particularly noteworthy.

The ONR's ASWT program heavily favors technology that supports gun systems, and this technology consists largely of "in-the-box"[1] and "stovepipe"[2] developments. A 1996 review group[3] reached a similar conclusion about the overall ASWT program. Although there is a valid niche for naval gun systems, it is addressed by current procurement and 6.4 programs. The ONR ASWT program should be more future-oriented and should address some important current and emerging weapon needs. For example, the Navy has a credible capability to attack stationary targets with a variety of weapons, but this capability is heavily dependent on the robustness of the Global Positioning System (GPS), and the Navy has no standoff, unmanned weapons to attack moving targets illuminated by moving-target-indicator (MTI) radar. The ONR ASWT program devotes only a limited effort to tasks that are directly responsive to a concept of operations that would allow a moving target to be attacked by weapons launched from ranges beyond the line of sight of the launch platform.

As weapon range requirements increase, there will be an increasing need to launch weapons on targets detected and held by sensors on platforms other than the weapon launch platform. The committee believes that the level of effort devoted to coupling detection systems on remote platforms to the targeting and fire control systems of Navy air- and surface-launched weapons is inadequate.

The current ONR ASWT program components in naval fire support are focused on increasing the range of hybrid, gun-launched, 5-inch missiles. However, the physics of the problem suggest that, as range and payload lethality requirements increase, surface-launched weapons should evolve into rocket-launched missiles. Although much of the current guidance work also applies to missile guidance, no work on imaginative solutions to the problems associated with the development of longer-range (> 100 nautical miles), small-diameter, ship-launched missiles was evident.

There was no evidence that an overall system analysis was done. This was particularly true for systems that in the future will of necessity rely on distributed sensors and data communications. In the committee's view, such an analysis would involve thinking through the entire weapons system (detection to target kill) into which a specific technology development might fit, and estimating the performance and cost parameter ranges that would make the technology acceptable.

The committee (as also the 1996 ONR Board of Visitors [BOV] review group) did not interpret the terms of reference of the study to include a major emphasis on affordability. However, cost and affordability are referred to throughout this assessment as an important factor in the overall weapons systems analysis recommended by the committee to support decisions on technology development.

The committee recommends that a significant portion of ONR's ASWT program be devoted to the exploration of new system concepts and components that support the need for long-range weapons with sufficient warhead yield and precision of delivery that can be launched from platforms outside the range of hostile defensive weapons. This approach is further elaborated in Chapter 1. Chapter 2 gives the committee's assessment and its recommendations for improving ONR's ASWT program. A common thread through these recommendations is the need for systems studies and analysis that involve other ONR codes with relevant responsibilities for overall systems definition. Similar commentary was provided by the previous review group.

The committee's recommendations are summarized as follows:

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[1]The term "in the box" means within the context of current program thinking.

[2]The term "stovepipe" refers to a program that stands alone, i.e., is constructed and supported to work by itself.

[3]The Office of Naval Research's Board of Visitors (BOV) review group, May 1996.

- *Air Superiority.* Taking into account the strong industrial capability in this area, institute systems studies to define sensors, weapons, and concepts of operations that will reduce the occurrence of short-range air-to-air engagements. Program component effort should continue toward significant and low-cost improvements in missile kinematics, seeker performance, off-bore-sight capability, and warhead lethality.
- *Precision Strike.* Conduct a study (drawing on the expertise of all relevant ONR codes) to define all components and their key characteristics (including latencies) of a responsive and precise robust sensor-to-target-kill (and damage assessment) chain that can engage ephemeral targets. Based on such studies, the cost-effectiveness of key technology enablers could be evaluated and a small number of investments made to bring 6.2 concepts rapidly to advanced concept technology demonstrations (ACTDs).
- *Naval Fire Support.* Rebalance the program components by increasing efforts on technology for surface-launched missiles for fire support at ranges beyond those expected for ERGMs. Increase the level of effort toward systems to attack moving targets. Provide sensors and final-stage guidance for autonomous or human-aided missile attack. Pursue technology for integration of emerging sensors and sensor-weapons communications.
- *Ship-based Defense.* Increase effort toward a layered defense against low-observable, low-altitude, maneuvering missiles in the presence of littoral clutter. Continue existing sensor-related efforts.
- *ASWT Supporting Science and Technology (S&T) (6.1 and 6.2) Program Areas.* Reduce the number of intelligent air vehicles and UCAV programs, and then redirect 6.1 and 6.2 program components toward closer coupling to other important needs of ONR's ASWT program. Surviving 6.1 candidate program components also should be scrutinized carefully for scientific merit.

1

Overview of the 1999 ONR ASWT Program Assessment

INTRODUCTION

The Office of Naval Research's (ONR's) Air and Surface Weapons Technology (ASWT) program resides within the Strike Technology Division of the Naval Expeditionary Warfare Science and Technology Department of ONR and accounts for approximately 25 percent of the department's budget. The goals of the ASWT program are to develop and transition enabling weapons technologies that provide the fleet affordable conventional weapons systems capable of meeting the need for upgrades of today's weapons and that lay the foundation for weapons of tomorrow. Within the ASWT program, technology investments are concentrated in the areas of guidance and control, fire control (including mission planning), aeromechanics, solid and air-breathing propulsion, ordnance (fuse/safe and arm/warheads), and naval gun systems and launchers. Overarching objectives for the different technology areas include affordability, signature management, longer standoff ranges, increased agility and maneuverability in the final stages of engagement, reduced time to target, increased lethality, and minimized collateral damage.

SCOPE OF AND APPROACH TO THE ASSESSMENT

The role of the ONR 6.2 (exploratory development) and 6.3 (advanced development) program areas in the ASWT program is to develop technology to meet future requirements of naval weapons research, development, testing, and evaluation (RDT&E). The role of the 6.1 program area is to support fundamental research underlying these development efforts. The 6.1, 6.2, and 6.3 programs must also provide support for and develop needed improvements to existing weapon systems. The committee believes that the overall ASWT program should also examine and explore opportunities in approaches not now pursued by the Navy or Marine Corps (in current prototype or production aircraft) either for budgetary reasons or because the impact of emerging trends in technology is not yet clearly visible.

Thus, the Committee on the Review of ONR's Air and Surface Weaponry Program took the approach that it was constituted to assess the extent to which ONR's ASWT program supported the

development of needed improvements to existing weapon systems as well as whether it was examining imaginative solutions to existing problems and was exploring possible solutions for emerging problems and future needs. In addition to assessing the relevance of ONR's ASWT program components to present and perceived naval needs, the committee also tried to determine if the supporting science and technology (S&T) (6.1 and 6.2) work pursued by ONR's Naval Expeditionary Warfare Science and Technology Department was at the forefront of technology in the fields involved, and the committee attempted to determine the degree to which ONR and its principal investigators were aware of or involved with similar work done elsewhere.

GENERAL OBSERVATIONS

Favorable Aspects of the ONR ASWT Program

Generally, most elements of the ASWT program were coupled to stated Navy and Marine Corps future needs, and specific opportunities for transitioning technology into naval weapon system development programs were considered in order that meaningful, exploitable technology development could be ready in time for introduction into these programs. In many cases, knowledge of parallel developments in other services or agencies was evident. The program also exhibited cooperation with industry and leveraging of industry independent research and development (IR&D). Also, the program components, for the most part, looked at the right time frame—far enough into the future without being futuristic. Although specific comments on individual program components are made in Chapter 2, the committee notes here its thought that the work on enhancements of the hybrid gun missile (extended-range guided missile [ERGM]) at the Naval Surface Warfare Center (NSWC) Dahlgren, which could be transferable to a pure missile system, was particularly noteworthy.

To overcome the inability to fund important program components adequately because available money must be spread over too large an area, ONR has recently adopted a top-level strategy of concentrating funding on specific, highly important naval capability shortfalls. These areas of funding concentration are called "spikes." Some of the ASWT program components seemed to be in "spike" areas (e.g., time-critical strike) and some (e.g., Global Positioning System [GPS] and integrated high-performance turbine engine technology) did not. The impact of the "spike" approach was not elaborated in the presentations made to the committee. Even though it will reduce funding in some areas now pursued, the "spike" approach was regarded by the committee as a good strategy that affords opportunities to accomplish important advances in a reasonable period of time in selected technologies.

ONR also recognizes that in certain areas other organizations (including industry) spend considerably more money than ONR can afford, and therefore ONR has elected not to do work in those areas. ONR, on the other hand, is funding efforts in areas important to the Navy and Marine Corps where other organizations are not likely to expend much effort. For example, traditionally the technology of air-to-air weaponry guidance and control, aerodynamics, and airframe technology has been developed by industry. On the other hand, to a large extent, warhead and propulsion technologies are not funded by industry. In these respects ONR's contributions are well invested.

The committee also noted that several recommendations of the ONR Board of Visitors (BOV) review group were implemented,[1] to the general benefit of the ONR ASWT program. Among these were relating the ONR program to specific naval needs and attempting to identify transition opportunities.

[1]See "Other Issues" following the next section.

Areas of Concern

The overall ONR naval fire support effort heavily favors technology that supports gun systems. The committee is deeply concerned about the complete lack of effort on alternatives to the 5-inch gun. Although further incremental improvements may be possible with this system, the committee believes that new approaches and technology will be required to satisfy future Marine Corps needs. Marine Corps doctrine is to use the V-22 to allow operations 200 nautical miles inland. If a 5-inch missile can be made with a kinematic range of 200 nautical miles, its payload will undoubtedly be zero. The naval fire support mission area will need to identify new weapons concepts to provide a transport system that will project militarily realistic payloads a distance of about 200 nautical miles. The ONR's naval fire support effort should be considering such capabilities. Currently, however, the naval fire support effort consists largely of "in-the-box" and "stovepipe"[2] developments in air-to-air weaponry. The 1996 BOV review group shared the perception that the overall ASWT program does not address some important emerging weapon needs. For example, although naval forces have a credible capability to attack stationary targets with a variety of weapons, they have no standoff, unmanned weapons to attack moving targets illuminated by moving-target-indicator (MTI) radar. The ONR ASWT program devotes only a limited effort to tasks that are directly responsive to a concept of operations that would allow a moving target to be attacked by weapons launched from ranges beyond the line of sight of the launch platform.

In the future, as weapon range requirements increase, there will be an increasing need to launch weapons on targets that are detected and held by sensors on platforms other than the weapon launch platform. The committee believes that the ASWT program contains an inadequate effort to couple detection systems on other platforms to the targeting and fire control of naval air- and surface-launched weapons. Unless they depart from the protective sanctuaries of altitude above the range of defense of shoulder-fired defensive missiles and employ command-guided weapons, naval aircraft have extremely limited capabilities to engage moving targets. If naval aircraft employ GPS-guided standoff weapons, they have no capability for the successful engagement of moving targets.

The Navy has an excellent capability for striking stationary targets. If GPS is not jammed, the Navy's GPS-guided weapons will hit the target GPS coordinates that they have been programmed to hit. However, if the target has moved between the time it was detected and the time that a GPS-guided weapon has been launched, the target will escape destruction.

Other than in future variants of the Tomahawk missile, no capability to retarget current GPS-guided weapons while in flight is planned. The accuracy of guidance and the delivery of weapons such as the joint standoff weapon (JSOW) and ERGM preclude the employment of unitary warheads in these munitions, which consequently are ineffective against hardened point targets. Finally, the Navy has no real capability to engage pop-up targets that emerge from hiding for only short periods of time.

Part of the problem perceived by the committee is structural within ONR and cannot be ascribed to deficiencies of the ASWT program. Work related to network-based targeting and network-centric warfare, mission planning, and autonomous target recognition is undertaken within other divisions of ONR. Nevertheless, the committee was concerned that there was little evidence in the material presented and discussions with ONR program managers that concepts for precision strike and naval fire support weapons were coordinated with work not managed by the ASWT program. Improved weapon kinematics and warheads are of little value if weapons cannot be guided to their targets.

Despite the fact that the current focus of the naval fire support mission area is increased-range hybrid gun-launched missiles, as range and payload lethality requirements increase, the physics of the

[2]These terms are defined in footnotes 1 and 2 in the Executive Summary.

problem suggest that surface-launched weapons should evolve into rocket-launched missiles. Although much of the current guidance work also applies to missile guidance, no work on imaginative solutions to the problems associated with the development of longer-range (> 100 nautical miles), small-diameter, ship-launched missiles was evident.

The committee found no evidence that overall system analysis was undertaken to think through the entire weapon system (detection to target kill) into which a specific technology development might fit and the estimated performance and cost parameter ranges that would make the technology acceptable. This was particularly true for systems that in the future will of necessity rely on distributed sensors and data communications.

The committee believes that a significant portion of the ASWT program should be devoted to the exploration of new system concepts as a basis for identifying the system concept and components that will allow the deployment of long-range weapons that can be launched from platforms outside the range of hostile defensive weapons, and that will deliver sufficient warhead yield[3] and have the necessary precision of delivery to allow the employment of unitary warheads that can engage hardened point targets. The committee also believes that ONR should perform systems studies to ensure that the weapon systems context in which it develops new technology is understood. Specifically the committee believes that more attention should be devoted to the following:

- Problems of targeting and interplatform communications;
- Specific weapons and weapons systems designed to reduce some acknowledged naval deficiencies such as attack of relocatable, moving, and ephemeral targets; and
- The synergistic relationship between surface-to-surface weaponry (Dahlgren) and air-to-surface weaponry (China Lake), not what the unique contributions, limitations (e.g., the fundamental physical limitations on gun-fired projectiles), or deficiencies of each were.

Although the committee was disappointed that fundamental issues relating to navigation assurance for weapons and weapons systems are de-emphasized in future ONR funding cycles because they are not one of the future naval capability "spikes," the committee recognizes that navigation assurance is receiving major attention by other organizations. The committee is cognizant of the fact that improvements to the robustness of the GPS (space component, waveform, and so on), sponsored from ONR's limited resources, would not add significantly to the remediation of this problem. However, in light of recent Defense Science Board and Naval Research Advisory Committee studies[4-6] that indicated the

[3]The lethality of a weapon depends on warhead yield (or weight W) and miss distance R. In recent years, the thrust of weapon design has concentrated on improvements to reducing R; however, for many targets W cannot be decreased. The committee believes that, in this respect, ERGM is a bad design compromise. With an approximate warhead weight of 10 kilograms and a delivery accuracy of approximately 20 to 30 meters, the designers have elected to use a submunitions payload that is ineffective against moving targets or bunkers and concrete structures. As a substitute for Marine Corps artillery to support engaged marines, it will have serious limitations since both R and W need improvement. Improving R will require advancements to the inertial navigation system, control authority, and control surfaces. Improving W will require better yield from the explosive (ONR's approach) and more payload volume. The latter requires a weapon of greater diameter, essentially a new weapon.

[4]Defense Science Board. 1995. *Global Positioning System, Phase I.* Office of the Under Secretary of Defense (Acquisition and Technology), Washington, D.C.

[5]Defense Science Board. 1997. *Global Positioning System, Phase II.* Office of the Under Secretary of Defense (Acquisition and Technology), Washington, D.C.

[6]Naval Research Advisory Committee. *GPS Vulnerabilities (Draft).* Department of the Navy, Arlington, Virginia, forthcoming fall of 1999.

vulnerability of basing U.S. weapon delivery methods largely on the GPS, ONR might consider initiating more extensive efforts toward the development of alternatives to the GPS to negate the drawback of GPS jamming. Thus, consideration might be given to terrain-aided navigation or to development of some of the novel techniques that were proposed in these reports.

The ASWT supporting S&T (6.1 and 6.2) work does not address weapons-relevant research topics such as enhanced control authority of guidance surfaces to improve delivery accuracy, efficient data links for target redirection and report, and ultralow-drift/low-cost inertial navigation system (INS) units. The committee thought that the 6.1 and 6.2 effort was too heavily oriented toward the functioning of an array of unmanned autonomous air vehicles. This effort does not give evidence of sufficient familiarity and involvement with work done by other organizations. In the intelligent air vehicles 6.1 area, although the principal investigators are well-known and competent members of the research community, the research does not appear to be at the forefront of technology. The committee believes that the number of projects in the intelligent air vehicles and uninhabited combat air vehicles (UCAVs) areas should be reduced, the surviving 6.1 work subjected to closer scrutiny for scientific merit, and then the ASWT supporting S&T program areas redirected toward closer coupling to other important needs of the ASWT program.

Other Issues

The suggestions and recommendations of the 1996 BOV review group[7] were read by the committee so that it could see the degree to which ONR had responded to those recommendations (see quoted material below). The BOV's statements and this committee's assessment of ONR's response follow:

- *"Little insight into project selection and program strategy."* This committee believes that in the current review, ONR did provide some insight into its strategy for selecting projects and program components. The focus, however, was mainly methodological, and the committee used its own judgment based on its expertise—naval operations, systems, and technology—to identify concerns and develop conclusions and recommendations in the specific areas presented.
- *"System trade studies need to be communicated."* This criticism is still valid today. This committee believes that ONR must perform some top-down system designs to determine how to fit 6.2 and 6.3 program components into a weapon system architecture.
- *"In spite of balance between S&T, work sounded evolutionary in nature. Focus appeared on short-term needs working old problems."* This committee believes that these observations are still valid. Stovepipe solutions rather than work relating to new operational concepts dominated the effort.
- *"Technology leveraging and connections to other services and IR&D not evident."* The committee believes that in general the ONR ASWT program has made an attempt to leverage work by other organizations and by industry IR&D. However, in some areas the ONR ASWT program does not seem to be as knowledgeable about and, hence leveraging, work done by other organizations as this committee believes it should be.

[7]Comments and suggestions by the BOV were included in the ASWT program triennial departmental review. Briefing to the Committee on the Review of ONR's Air and Surface Weaponry Program by Mr. David Seigel of ONR, May 26, 1999.

- *"Little indication of direct contact with customers, working on real needs."* The committee believes that ONR now maintains adequate contact with customers and, for the most part, works on real needs.

The above comments on the ONR ASWT program taking into account the previous review group's recommendations are not inclusive. The previous group also made additional comments on topics that this committee did not review. No comments are made in this report about these issues.

2

Assessment of the ONR ASWT Program

INTRODUCTION

The Office of Naval Research's (ONR's) Air and Surface Weapon Technology (ASWT) program addresses a range of technology issues related to weapons for air superiority, precision strike, naval fire support, and ship-based defense. In addition the program includes 6.1 and 6.2 supporting science and technology (S&T) program components related to the operation and control of uninhabited combat air vehicles (UCAVs). Of necessity the coverage of these areas (air superiority, precision strike, naval fire support, ship-based defense, and supporting S&T) by ONR's ASWT program is not comprehensive.

AIR SUPERIORITY

Overview

Air superiority depends on many factors, including pilot training and tactics, aircraft signature suppression, airborne sensors, support by early warning sensors, effectiveness of suppression of enemy air defense (SEAD), efficiency of air-to-air-weapons, and the effectiveness of electronic countermeasures. In the mission area of air superiority, ONR's work is focused only on air-to-air weapons, directed exclusively to the following themes:

- Rocket propulsion technology,
- Missile kinematics,
- Seeker performance,
- Ordnance lethality, and
- Affordability.

Air-to-air weapons are common to both the naval air forces and the U.S. Air Force, neither of which can act independently in regard to their development. The overall air-to-air weapons thrust of the naval

air forces, the U.S. Air Force, and ONR is to continue with existing AIM-9X- and AIM-120-class missiles and to concentrate on preplanned product improvements (P^3Is) in the areas of propulsion, off-bore-sight capability, hard-kill countermeasures, and integration into a network-centric model. The stated long-range goal is to have a single, dual-range, air-to-air weapon by about 2015.

Given the recent history of air warfare, these objectives may seem to be legitimate. Since the war in Vietnam the United States has not lost a fighter in air-to-air combat. However, the United States may have been lulled into a false sense of security. Recent advances in foreign air-to-air missiles such as the AA-11 and Python-IV find the U.S. Navy lagging in several areas of missile performance. In the continuum of air warfare, U.S. capabilities that include the airborne warning and control system (AWACS), electronic intelligence (ELINT), National systems,[1] aircraft performance, electronic warfare, and pilot training have given this nation an edge that has resulted in an enviable record in recent air combat.

Comments on Program Components

With such supremacy in air-to-air combat and the heavy emphasis on strike warfare, the natural tendency is to assume continued supremacy and devote fewer resources to air-to-air missiles and their capabilities. However, the Navy and Marine Corps especially could be faced with a worthy opponent in a come-as-you-are fight, without the vast support resources that have come to be expected and demanded since the Persian Gulf and Kosovo engagements. For this reason, the committee believes that the ONR ASWT program must continue to maintain detailed awareness of the technical developments of other countries and must ensure that U.S. capabilities under development are at least as good as those, if not better.

The air-to-air weapons component of ONR's ASWT program is designed to be evolutionary in nature. Performance improvements have been incremental but steady. The technology being used is at the forefront of propulsion and warhead technology. Current weapon performance is significantly better than it was 10 to 15 years ago. The ONR ASWT program has time-phased goals for 5, 10, and 15 years into the future. Although goals such as a 25 percent increase in weapon range (for the same weapon volume) and a 15 percent increase in weapon velocity may seem relatively modest, meeting them may well make the difference between success and failure in air-to-air combat.

Air-to-air weapon research is a relatively mature field where current weapon capabilities may be well up on the curve of realizable performance. The committee believes that as long as modest, but significant, improvements in performance can be achieved at reasonable cost, the ONR ASWT program should continue to support such work. However, the committee cannot escape questioning the merit, on these terms, of some of the current effort. For example, success in a short-range air-to-air encounter depends among other things on how far off bore sight an infrared (IR)-guided weapon can be fired. If one asks what an incremental improvement in an off-bore-sight capability translates into in the time domain, the answer is generally about a few tenths of a second. While the ONR ASWT program is addressing this problem with considerable success, the committee does not find very reassuring the prospect of future air superiority depending on such marginal gains in capability. The committee

[1]The term "National" refers to those systems, resources, and assets controlled by the U.S. government, but not limited to the Department of Defense (DOD).

recommends that ONR devote more effort to the development of improved sensors and weapons that will provide situational awareness such that (even under restrictive rules of engagement) air targets can be engaged at much longer standoff ranges than current capability permits. Naval forces depend on short- and medium-range weapons today because of limits imposed by the rules of engagement. As a result, engagements occur with weapons that do not offer significant performance margins over those of potential adversaries. Being able to fire 5 degrees further off bore sight will not give a robust margin. New approaches should be sought toward meeting the objective of eliminating close-range air-to-air engagements, and the survival of U.S. aircraft should be supported by more than a marginal enhancement of current off-bore-sight capability.

The committee was surprised to learn that the ONR ASWT effort did not include evidence of lessons learned from available information on Russian missiles, nor of incorporation or reverse engineering of Russian missile advantages into U.S. missiles.

In the area of seeker performance the committee is convinced that the United States must not lose its advantage in acquisition range. Information on off-bore-sight angle acquisition and track capability should be shared with those friendly air forces that may have capabilities that exceed those of the United States.

The United States holds advantages in ordnance lethality, and ONR's efforts in this area are exciting, particularly with respect to accuracy and payload size. Missile size is important, particularly in stealth platforms with internal carriage requirements. If a missile cannot be accommodated internally in a stealth aircraft, much of the advantage of the stealth treatment may be lost.

One area not mentioned in the ONR ASWT review presentations related to air-to-air guns. It appears that U.S. leadership in this area of former dominance has been ceded with the announcement of the gun selection for the Joint Strike Fighter. The ONR ASWT program does not appear to be considering the development of a follow-on gun to the widely successful M-61-A1 cannon.

Conclusions

The committee's conclusions for the air superiority mission area of ONR's ASWT program are the following:

- Improvements continue to be needed in missile kinematics, enhanced seeker performance, increased off-bore-sight capability, and enhanced warhead lethality.
- Efforts should be increased toward sensors, weapons, and concepts of operations that will allow engagements at ranges beyond those currently projected for missiles, with the objective of reducing the occurrence of short-range air-to-air encounters.

Recommendations

Air Superiority. Taking into account the strong industrial capability in this area, institute systems studies to define sensors, weapons, and concepts of operations that will reduce the occurrence of short-range air-to-air engagements. Program component effort should continue toward significant and low-cost improvements in missile kinematics, seeker performance, off-bore-sight capability, and warhead lethality.

PRECISION STRIKE

Overview

The major problems encountered by the Navy and the Marine Corps in the mission area of precision strike are related to the following:

- Targeting of fixed, relocatable, moving, and ephemeral targets;
- Automatic target recognition (ATR);
- Response time for delivery of weapons to the target;
- Warhead lethality;
- Weapon range; and
- Weapon guidance.

The current ensemble of precision strike weapons is usually considered to include accurate air-launched weapons (laser-guided bombs, the standoff land-attack missile [SLAM (ER)], the joint stand-off weapon [JSOW], the joint direct-attack munition [JDAM], the high-speed antiradiation missile [HARM] and sensor-fused weapons [SFWs]), and variants of the Tomahawk missile.

In the area of precision strike, ONR's ASWT program is focused on the following themes:

- Responsive and accurate fire control,
- Precision target handoff, and
- Weapon sensor performance.

When fixed targets are attacked, the guidance of existing weapons is generally dependent on a guidance system that uses an inertial measurement unit (IMU) that is updated by Global Positioning System (GPS) measurements. Image correlation techniques are also used for terminal homing. Weapons, such as HARM, home on the radiated signature of their intended target. Sensor-fused weapons operate on a variant of ATR, in the sense that they recognize and home on specific features of the target's signature (acoustic spectrum or IR signature).

Jamming is a problem for some GPS-guided weapons. Of all the GPS/IMU-guided weapons, the performance of the Tomahawk missile is the most robust in the presence of GPS jamming. JDAM with short-range GPS/IMU guidance is also relatively immune to jamming. Unfortunately, the performance of many other U.S. GPS/IMU-guided weapons would be degraded by GPS jamming.

If the effects of GPS jamming cannot be mitigated, many U.S. GPS-guided weapons will be ineffective. Approaches to mitigation of the effects of GPS jamming include an increase in the power radiated from the satellite, the use of alternative navigation systems such as terrain-aided navigation, null-steering antennas, pseudolites, improved signal processing, and extremely low-drift IMUs. Although a program in GPS anti-jam technology exists within ONR's precision strike area, navigation assurance is not one of ONR's major thrusts or "spikes."[2]

If a target is relocatable, the problem is basically one of improving system reaction time in a series of interrelated definable steps. A relocatable target must first be geo-located by a sensor system. Target coordinates must be passed to strike planners who must then designate mission responsibility for

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[2]This concept is discussed in Chapter 1, in the section "Favorable Aspects."

engaging the target to a weapon-launching aircraft, to a Tomahawk-type missile, or to an extended-range, guided missile (ERGM) firing platform. The objective (allowing for the time of flight [TOF] of the weapon to the last known target location) is to shorten the entire time of the chain of events from target detection to target kill, including the weapon's TOF, so that the target does not have a chance to relocate or hide before the weapon arrives. If the target has relocated (or was originally in motion when first detected) its position must be reacquired by a sensor, and new target coordinates must be provided to either the weapon in flight or its launch platform, or both. To achieve the affordability objective, there is an inherent need for a low-cost data link to a weapon in flight so that it can be redirected to a position such that the weapon's sensors can reacquire a relocated or moving target. This issue is not being addressed in ONR's ASWT program.

Ephemeral targets represent an extreme example of a relocatable target in the sense that they are exposed to detection for periods of time that are short compared to the TOF of even hypervelocity weapons. Such targets can be destroyed only when a loitering platform with an appropriate sensor can detect the target and provide information that will initiate the launch of or guidance for in-flight short-TOF weapons.

Clearly the most significant problems in precision strike are those of command, control, communication, and intelligence (C^3I). The internal taxonomy of ONR is such that issues related to C^3I are not the responsibility of the ASWT program. A coherent program component that addresses the critical problem areas that need attention in both precision strike and naval fire support does not exist within ONR.

The ONR effort in precision strike consists of several program components with specific performance goals, base lined relative to 1995 weapon capabilities and time phased for completion by 2005, 2010, and 2015. The ASWT program's systematic linking of goals, objectives, technical challenges, and approaches (GOTChA), summarized in a chart presented to the committee, appears to be a useful technique for defining a path to future weapon technology. However, as presented, the flow-down pattern displayed within the individual GOTChA charts in the precision strike mission area tended to expand into what appeared to be a varied and disjointed set of projects that were force-fitted into the related GOTCHA chart. Some of these efforts appeared to have been created with clear goals in mind. However, others appeared to have been allowed to proceed in isolation, without consideration of emerging alternatives and advances in the areas originally addressed. For instance, the "target/weapon pairing rate" and "GPS guidance" performance goals for 2005 as stated in the presentations on precision strike will be greatly exceeded in 2003 by the planned Tactical Tomahawk System without any need to benefit from ONR's technology effort. Although it may simply represent a failure in communication, this discrepancy leads to uncertainty about the coherence of the overall approach, in a broader view, and the value of some specific efforts.

As a total set, the precision strike systems concepts did not appear to be sufficiently "system engineered" to allow a meaningful evaluation of the technologies' potential to evolve into an affordable set of strike weapon systems. Some of these components might appear to offer the Navy and Marine Corps the prospect of a significant enhancement in warfighting capability. However, they will be non-contributors if they require major breakthroughs in other technology, or if they require unaffordable changes in other systems needed to support the use of the new technology.

The committee suggests that ONR support systems studies to identify the utility of some of the specific technologies in which it is investing its funds. A case in point might be an analysis of a program component for the development of hypervelocity weapons. The first issue to be resolved would be how the targeting process for such a weapon concept would operate. Would there be a maximum allowable time for mission planning after target detection? If that time budget were not achieved, would the

hypervelocity weapon still have tactical value? If so, how would the required reduction in the mission planning cycle be achieved? Systems studies focusing on such questions might result in a refinement of system concepts so that quantitative evaluations could then be done. Such studies would enhance critical decision making about which concepts to continue and which to abandon. An investment of this nature by ONR would provide a good return to ONR management as well as provide a quantitative rationale for technology transfer to key acquisition programs.

It appeared to the committee that the overall set of precision strike projects could have a closer correlation with the ongoing acquisition programs they propose to augment in the future. Based on the material presented in the review, the committee concluded that a better alignment of the technology developments with the plans, goals, and schedule of these acquisition processes would focus investment toward those high-payoff concepts that have a reasonable chance of making a transition into the targeted acquisition programs. As a technology matures it must become increasingly aligned with the acquisition schedule. At the point of highly probable transition it must become incorporated into the acquisition schedule. This approach would present greater opportunity for ONR 6.3 and advanced concept technology demonstration (ACTD) efforts to join with, or serve as surrogates for, acquisition, demonstration, and validation, which have been largely eliminated by acquisition reform.

Comments on Program Components

Because of the diversity and extent of the program components in the precision strike area, the committee believes that it is appropriate to comment on each of the individual major efforts being pursued in this mission area.

LADAR Automatic Target Recognition for Cruise Missiles

The use of lasers on weapons has advantages in that they measure geometry, which is inherently stable. However, in the design of a weapon sensor to detect a mobile or moving target, consideration must be given to the overall system. The LADAR concept described in the program review might be useful. However, it is the committee's belief that the requirements need to be better understood. Answers should be provided to questions such as the following:

- What is the allowable false alarm rate?
- What is the required probability of correct identification?
- What other inputs can be used to augment the seeker?
- What sensor range is required under what weather conditions?
- Can other systems be used to narrow the search pattern and reduce the seeker requirement?

A system study would indicate what target accuracy and what precision of target identification are achievable. Better targeting accuracy and increased precision of target identification would help to reduce the number of weapons expended on decoys and other false targets, increase the probability of correct identification, and relax the range requirement on the sensor. Understanding the context will crystallize the requirements for, and focus the design of, a seeker.

The objective of this effort should be to develop a single sensor that can operate within a system (including reconnaissance sensors, command and control [C^2], planning, and weapon seekers) to kill multiple movable or moving targets inexpensively.

The committee suggests that this effort be continued, and be supported by a re-evaluation of the total system concept.

Responsive and Accurate Fire Control

The committee found the discussion of this program component to be confusing, with several different objectives appearing to be intermingled. This apparently overarching program component includes the four tasks discussed immediately below.

Precision Standoff Weapon Control

The presentation on precision standoff weapon control made reference to the automatic generation of templates that would simplify the reporting over a weapon data link of data related to objects detected in the field of view of a weapon's sensor. This task will result in the achievement of an impressive capability if the predicted results can be realized. It is the committee's judgment that this task should be pursued to completion.

Land Attack Battle Damage Indication

The approach taken to battle damage indication appears to be appropriate. The work on high-range-resolution synthetic aperture radar under this task is generally well thought of in the precision strike community. The particular work discussed in the presentation to the committee may be somewhat dated because of the new Sandia Lucid Eyes system for land battle damage assessment. No contractor was mentioned in the presentation; however, Sandia National Laboratories is doing excellent work in this area with the specific application of Lucid Eyes. The committee suggests that the need for this task be re-evaluated in view of other work being done by other performing organizations.

Precision Target Handoff

The objective of the work under this task is precision target coordinate description and handoff for first-pass attack capabilities against targets of opportunity. The effort appears to be very similar to the controlled imagery rapid targeting approach being developed under the sponsorship of the Naval Air Systems Command (PMA-281). Based on the presentation, the goal is to get the target information into an airborne platform. Given that the efforts appear to be duplicative in some areas, the complementary nature of the tasks should be investigated. The committee suggests that this task be continued subject to a re-evaluation to determine if duplication of effort exists.

Tomahawk-Predator Advanced Relative Targeting

The concept of Tomahawk-Predator advanced relative targeting (TOPART) requires significant coordination between uninhabited air vehicles (UAVs) and incoming missiles. Conceptually, ship- or air-launched missiles must arrive within 10 minutes of identification and geo-location of a target by a UAV. Depending on the shooter-to-target range and on the weapon's velocity, this constraint might imply that a missile must be launched before the target's coordinates are actually obtained. Because UAVs are slow there could be significant time lags between different aim-points. It is not clear that a

system concept has been developed or that one exists that is practical. Questions to consider are the following:

- How is the UAV initially cued?
- What type of target is under consideration?
- Are ground observers designating time-critical targets?
- Can the UAV get there in time?
- What are the volume and speed of the aim-points generated versus the requirements?
- How dependent is the UAV on the GPS, and what is the impact of GPS jamming?
- Does this concept represent a significant improvement in accuracy over current systems coupled with anticipated improvements in GPS?

The committee suggests that this task be re-evaluated from a total system perspective. The committee suspects that the view of the component might be too restrictive or that it might have an inherent capability to address a broader situation than the one presented.

Weapon Sensor Performance

The objective of the weapon sensor performance program component is to maintain a 3-meter circular error probable (CEP) in the presence of adverse weather, clutter, and GPS jamming.

Three approaches to this ensemble of problems are being considered. One approach is to develop an inexpensive millimeter-wave seeker to increase weather penetration and to apply microelectromechanical system (MEMS) technology to aircraft and missile antennas to reduce costs. The millimeter-wave sensor and the employment of MEMS technology are sound ideas. However, the work as presented might have been overtaken by events. Some excellent work sponsored by the Defense Advanced Research Projects Agency's (DARPA's) Discoverer II—global moving-target-indicator (MTI) radar constellation—program will demonstrate, at the end of 1999, results based on the same approach. The committee suggests that this particular effort be re-evaluated in light of progress made by other organizations.

In an effort to improve seeker performance in the presence of clutter and GPS jamming, specific signal-processing algorithms have been selected for implementation. The one being implemented for the purpose is one of the better algorithms. It is very fast, is of good quality, and directly supports progressive transmission. The effort described to the committee in the presentation is scientifically and technically sound and shows progress toward meeting the objectives.

The committee hopes that ONR's efforts to produce robust, fast, noise-free compression for low-bandwidth transmission will continue to be supported along with the effort to develop a robust embedded zero-tree wavelet compression algorithm such as that described in the presentation to the committee.

The committee believes that ONR's work on negating GPS jamming is of excellent quality but is inadequate in its scope. Specifically, it does not include development of high-performance nulling antennas for small-diameter weapons, application of coating technology to increase the value of body shielding, development of deep integration of GPS and the inertial navigation system (INS) through the application of improved Kalman filters, and development of an ultralow-drift, cheap INS.

The work on bio-vision processing is attempting to identify and select a target aim-point with minimum computer capability. The approach is to examine analog and digital signal processing based on insect models, and then to transfer fly-eye strategies to IR focal phased array sensors in weapons. The work is interesting and imaginative, but based on the material presented, it is not clear that emulat-

ing an insect's visual processing will help with target identification, target tracking, and/or clutter cancellation.

Hypersonic Strike Weapons

One of the major goals of ONR's ASWT program is to develop, by 2015, a family of responsive air- and ship-launched weapons that have fly-out ranges that are 200 percent greater than the ranges of 1995 baseline weapons, and average velocities of Mach 8. These goals are based on a scenario that assumes that a naval task force will be constrained, by the need for self-protection, to operate 100 nautical miles from the shore. (The committee notes in passing that this scenario is at variance with the ERGM scenario, which assumes that naval fire support platforms will operate 25 miles from the coastline.) In this scenario, the naval task force must provide fire support to locations 200 miles inland. The weapon range must therefore equal 300 nautical miles. The second assumption of this scenario is that fire support must be delivered to the target within two and one-half minutes after the initial call for fire.

The scenario appears to assume that the command-and-control process has zero latency; that is, a call for precision strike fire support is presumed to be responded to instantaneously. This implies a mean speed of 7,200 knots, which equates to Mach 11.4. If the TOF delay can be extended to 3.75 minutes, the required mean speed would drop to an equivalent of Mach 8 (at 115,000 ft if the dynamic pressure is held constant at 500 pounds per square foot).

The missile system described to the committee was powered by an integral boost dual combustion mode ramjet. After booster burnout, fuel is injected at an aft set of injectors and the propulsion unit acts as a classical subsonic burning ramjet. At some high Mach number, say 6, fuel is also injected at a forward set of injectors, and the fuel flow rates in the two injectors are controlled so that the propulsion system acts as a supersonic combustion ramjet, a so-called SCRAMjet. While subsonic combustion ramjets are fairly well understood, and have powered deployed supersonic weapons systems, this is not the case for the SCRAMjet or the dual combustion mode ramjets. The committee found no information in the open literature suggesting that subsonic combustion ramjet operation has successfully transitioned to a SCRAMjet. The committee suggests that additional experimentation and research be done prior to committing a new weapons system development to the dual combustion mode ramjet.

The proposed dual combustion mode ramjet would use standard hydrocarbon fuels. This has the potential to present launch-on-command problems, which can be overcome by use of a solid propellant and a configuration called an integral rocket ramjet. The hydrogen-rich rocket exhaust is burned in the duct downstream of an air inlet. Such systems have been successfully flown at hypersonic speed by the U.S. Air Force and have been used by the Russians in the SA-6 missile. The committee suggests that this configuration should be examined as a candidate near-term, quick-reaction weapon. Alternatively, it may be useful to look at the use of a ballistic rocket exo-trajectory for application to this weapon system.

Conclusions

The committee's conclusions for the precision strike mission area of the ONR ASWT program are the following:

- To meet top-level requirements (performance goals), an effort is needed to define future strike weapons systems concepts. Such a definition should include all components (including limitations on system latency) of a responsive and precise sensor-to-target-kill chain that can engage ephemeral

targets. Dependence on GPS robustness, and the possibilities of alternatives to GPS, should be explicated in the concept definition.

- Also needed are an evaluation and survey of technology enablers for each major weapon system concept ONR is supporting. As an example, what role do weapons data links and seekers play in the total system, in achieving cost-effective, precision capability?

Recommendations

Precision Strike. Conduct a study (drawing on the expertise of all relevant ONR codes) to define all components and their key characteristics (including latencies) of a responsive and precise robust sensor-to-target-kill (and damage assessment) chain that can engage ephemeral targets. Based on such studies, the cost-effectiveness of key technology enablers could be evaluated and a small number of investments made to bring 6.2 concepts rapidly to advanced concept technology demonstrations (ACTDs).

NAVAL FIRE SUPPORT

Overview

Both the naval fire support and the precision strike mission areas face a common set of problems related to the targeting of fixed, relocatable, moving, and ephemeral targets; automatic target recognition; response time for delivery of weapons on target; warhead lethality; weapon range; and weapon guidance. Modern concepts of naval fire support are based on the evolution of the ERGM, which is a 5-inch-diameter, GPS-guided missile that is gun- rather than rocket-launched. Current ERGM designs have a range of about 63 nautical miles. If current efforts in the naval fire support mission area are successful, ranges of about 100 to 200 nautical miles may be achieved within the next 15 years.

ONR's ASWT program in the area of naval fire support is focused on the following themes:

- Weapon responsiveness,
- Rapid and accurate targeting,
- Improved lethality, and
- Cost-effective sustainability.

The range of the ERGM weapon and its successors allows attacks on targets that are beyond the line of sight. Thus the naval fire support problem of guiding a weapon to a target is identical to the problem in precision strike.

Comments on Program Components

The committee found much of the work in support of ERGM-like weapon systems to be technically superb. However, the committee was concerned about what the work on the 5-inch round will contribute to improved weapons capability. The technology of the gun-launched missile appears to be well up on the knee of the curve—the technology is exquisite, but what will happen if the range to target grows by a factor of, say, two? If marines are engaged in combat in Kosovo, the range of the ERGM round or any of the derivatives presented at the review will be inadequate. The committee believes that it is in part ONR's mission to be thinking about how this problem will be resolved with future weapons systems.

The naval fire support effort heavily favors the technology that supports improving naval gun performance capabilities through increasing the range and reducing the CEP when firing on coordinates. The committee regarded the NSWC Dahlgren 6.3 program component as particularly good in this respect. However, the committee thought that the scope of the naval fire support effort was too narrow and offered up only "stovepipe" solutions. The program components did not address important current and emerging weapon system needs.

Underlying most of the naval fire support R&D was the assumption that Navy ships would be stationed some 25 nautical miles offshore and would be called upon to fire on designated (GPS) target coordinates that would somehow be available (probably from a forward observer). The objective is to deliver (small) warheads with small CEPs rapidly at a high rate of fire. The effort shows little evidence that the entire integrated sequence of detection, classification, target designation, communication of targeting information from the several surveillance sensor systems, and weapon response has been considered as an overall system.

As weapon range requirements from offshore platforms increase, the limitation of gun launch forces a reduction in warhead size that essentially no practical amount of reduction in CEPs can offset. Requirements for increasing weapon range render the gun as the first stage of what would otherwise be a rocket solution. All-rocket weapons might be more effective for the long-range delivery of larger warheads to more distant targets at a higher rate of fire. In this respect the concentric canister launcher has merit. The naval fire support mission area needs more emphasis on missile solutions.

The naval fire support mission area is also deficient in providing program components that address moving targets. Although the naval forces have a credible capability to attack stationary targets with a variety of weapons (mostly air-launched), they have no standoff, unmanned weapons to attack moving targets illuminated by MTI radar. The ONR ASWT program devotes only a limited effort to tasks that are directly responsive to a concept of operations that would allow a moving target to be attacked by weapons launched from ranges beyond the line of sight of the launch platform.

Also, there is insufficient emphasis on a capability for attacking targets other than those for which the coordinates are given. In land warfare supported with naval fire, a soldier or marine close enough to the target to provide its coordinates may also be close enough to use a (laser) target designator. In addition, the target may have specific sensor-significant attributes (heat, radar return). Thus, a portion of the naval fire support mission area should address weapons that can perform either autonomously or with human-aided terminal guidance. Such a capability would also go a long way toward addressing moving targets or targets that have relocated during the time elapsed from target designation (by land forces) to weapon arrival time.

The committee thought that the weapon guidance program components were valuable. Although several of the low-cost guidance systems are being developed for gun munitions, they are equally applicable to surface-to-surface missiles. In fact, the attempt to reduce costs for guidance systems so that they are affordable for gun munitions might lead to missile guidance systems with lower costs than those achievable by a missile guidance cost-reduction program.

Conclusions

The committee's conclusions for the naval fire support mission area of the ONR ASWT program are the following:

- The R&D portion needs to be better balanced by increasing the level of effort devoted to surface-launched missile solutions to naval fire support;

- Naval fire support weapon system concepts are needed to enable the engagement of targets at ranges that exceed any extrapolation of ERGM ranges;
- Weapon sensors and terminal guidance systems are needed to provide for autonomous attack of sensor-significant targets or to respond to cooperative targeting with human-aided target designation;
- An increase in the level of effort on systems designed to attack moving targets is needed; and
- An overall increase in systems engineering is needed to ensure that emerging sensors, third-party (non-organic) targeting, and sensor-to-weapon communications are integrated into proposed R&D solutions.

Recommendations

Naval Fire Support. Rebalance the program components by increasing efforts on technology for surface-launched missiles for fire support at ranges beyond those expected for ERGMs. Increase the level of effort toward systems to attack moving targets. Provide sensors and final-stage guidance for autonomous or human-aided missile attack. Pursue technology for integration of emerging sensors and sensor-weapons communications.

SHIP-BASED DEFENSE

Overview

In the mission area of ship-based defense, the generic problem is to increase the ability of existing ship self-defense systems to maintain (and improve) current levels of performance in the face of threat missiles with decreased radar cross sections, reduced altitude trajectories, and higher agility. A conscious decision has been made to limit the ONR effort in this area to the examination of a few novel concepts for terminal and intermediate-range defense systems. These program components are of interest in that they deal with an important niche market in the field of ship self-defense. However, they do not address the most significant problems, such as countering low-observable, low-trajectory, or maneuvering missiles except in intermediate and terminal engagement phases.

In recent times, ship self-defense has come to mean defense against air- and surface-launched weapons. Ships are of course subject to attack by torpedoes. The committee notes in passing that no ONR-sponsored work related to torpedo defense was described during the review. Although this omission was undoubtedly an artifact of ONR's organizational structure (i.e., torpedo defense is not a responsibility of ONR's Naval Expeditionary Warfare Science and Technology Department, of which the ASWT program is a part), it is the committee's belief that commenting on the overall value of the effort in ONR's ship-based defense mission area would be inappropriate since a significant portion of the problem is not addressed in a coherent program component.

The defense of a ship in the littoral areas of the world is a difficult task because of the variety and number of threats possible. The overall ONR effort in this regime encompasses an eclectic mix of technologies that reflect the diversity of these threats, which range from sea-skimming and ballistic missiles and land-based artillery to massive attacks by suicidal fanatics in small boats and water jet craft, and so on. Coupling these with the possibility of intense, high-power jamming gives an appreciation of the magnitude and danger of the potential threat.

Comments on Program Components

In ONR's ship-based defense mission area, the program components span two of the three main areas of ship defense, which are terminal defense (range less than 1 kilometer), intermediate defense (range out to 5 nautical miles), and extended-range self-defense (ranges greater than 5 nautical miles). The requirements for defense with respect to reaction times, warhead lethality, and so on vary depending on where the defensive action takes place. Program components have been structured to reflect these conditions based on input from a 1998 workshop that included resource sponsors and program executive offices (PEOs).[3] The outcome of the workshop was that future technology efforts should focus about 50 percent on near-term technologies that can be used by engineering and manufacturing development programs and 50 percent on long-term S&T initiatives that can be applied to future naval requirements.

The briefings presented to the committee included recently completed as well as ongoing tasks. Among the former were work on terminal-defense technologies like the Firebox composite gun, the semiactive radio frequency (RF) millimeter-wave projectile guidance system, and the water-barrier terminal-defense system. All three of these systems could provide developed technologies that might be applied now and in the future. The Firebox composite gun consists of multiple barrels (9 to 16), each of which can fire a 60-mm semiactive, hit-to-kill guided projectile at a launch energy of 4 to 5 megajoules. Thus it has a launch energy one-half that of the MK 45 5-inch/54 with one-tenth the weight of the 5-inch barrel and with multiple barrels can outperform the 5-inch gun for close-in defense. The projectiles were guided by a W-band radar. The water-barrier system, recently completed, is a last-ditch option in a layered defense concept. Tests and models indicate the viability of the concept in favorable geometries.

Ongoing tasks in this mission area include technologies in sensors, particularly low-cost wideband seekers; warheads; and novel propulsion methods. These technologies should find application in gun-launched projectiles as well as missiles.

Numerous studies[4] have shown the effectiveness of guided rounds for close-in defense against sea-skimming missiles. In all cases detection in the presence of low-angle background clutter characteristic of littoral sea areas is a critical factor. This is also true for detection of high-speed surface craft. While the ship defense program component includes efforts to characterize low-angle propagation and clutter for radar and IR in littoral environments, the criticality of the problem indicates the need for a major effort in this area.

Reactive-material warheads represent a promising technology because of the enhanced energy deposition that results on impact, including the kinetic energy of the fragments, the chemical explosive energy of the reactive elements, and the potential for release of energy due to the combustion of gases and materials. This translates into a two- to four-fold increase in destructive energy compared to the kinetic energy alone. Of several different reactive materials, only a limited number can survive an explosive launch. In fact, only aluminum polytetrafluoroethylene was found to not react when explosively launched, but to react when it struck a target. This technology program component is aimed at developing a notional warhead that incorporates reactive materials. Its effectiveness will be demonstrated in static arena tests.

[3]ONR-35 Ship Defense Workshop, May 19, 1998. Attendees included RADM Baslile, USN, from NAVSEA, and representatives from N865, N86T, N911, OUSD/DDR&E, ONI, PEO TSC, NSWC, NAWC, and ONR 31 and 35.

[4]Dawson, V.C.D., J.D. Love, C.A. Carney, G. Schecter (Battelle), C. Sharn (SDIO), D.S. Malyevac (NSWC), J. Connelly (SAIC), and G.J. Ferrebee (NSWC). 1990. *The Naval Gun Study, Vol. 1: Summary*, Center for Naval Analyses, Alexandria, Va., October, 1991. Dawson, et al. *Vol. II: Support Analyses*, August, 1992.

The rolling airframe missile (RAM) accelerator gun is a novel approach to achieving very high velocities (Mach 6+) in a terminal-defense system, thereby decreasing TOF and increasing keep-out range. There are engineering problems associated with a system of this type, particularly when a high rate of fire is desired. It also involves a special projectile shape, which may be costly.

ONR has done an excellent job of restructuring its ship-based defense program components using the input from Navy resource sponsors and PEOs referred to above. In addition it has mandated progress reports and milestones with clearly defined completion dates. The program components in this ONR mission area involve many diverse technology areas but seem to be well balanced with clearly defined goals and objectives.

The committee recognizes that the development of new technologies frequently requires many years of effort and funding. During such times the requirements often change because of new PEOs or sponsors, whose priorities differ from those represented by a particular technology. Thus, technologies like Firebox and the water-barrier terminal-defense system are currently on the shelf because of the Navy's emphasis on missile solutions to ship defense involving the evolved sea sparrow missile and the RAM, which are more attuned to the blue water threat. As emphasis on littoral warfare increases there will be an increased need for a time-critical layered defense at least three engagement levels deep. The technologies mentioned could provide a cost-effective solution.

The committee notes in passing that the anti-ship cruise missile problem is still not solved. Although the combined effectiveness of U.S. long-range defenses, intermediate-range defenses, and terminal defenses presents a high cumulative probability of ship survival, the success rate is still less than perfect. The committee also recognizes that the Navy has evinced little interest in making major new investments in terminal-defense systems and that the ship-based defense mission area is undergoing an orderly redirection. The committee hopes that the sensor work described in this review will survive program component reorientation and be applied to other defense applications as appropriate.

Conclusions

The committee's conclusions for the ship-based defense mission area of ONR's ASWT program are as follows:

- An effort is needed to develop a layered defense for countering low-observable, low-trajectory, and maneuvering missiles. Such a defense should not be limited to the terminal engagement phase of ship self-defense.
- A major effort is needed to detect low-flying missiles and high-speed surface craft in the presence of littoral clutter.
- Continuing support is needed for the sensor work described in this review so that it will survive program component reorientation and be applied to other defense applications as appropriate.

Recommendations

Since many of the tasks reviewed in the ship-based defense mission area have been completed, and since the program components are undergoing a substantial redirection, the committee did not believe that major recommendations were appropriate in this area.

Ship-based Defense. Increase effort toward a layered defense against low-observable, low-altitude, maneuvering missiles in the presence of littoral clutter. Continue existing sensor-related efforts.

ASWT SUPPORTING SCIENCE AND TECHNOLOGY (6.1 AND 6.2) PROGRAM AREAS

Introduction

The ONR ASWT program includes a supporting 6.1 and 6.2 effort described as being devoted to air platform and weapons technology needs not addressed by other ONR departments.

The ASWT 6.1 program area has three main research components:

- Shock-induced fluorine chemistry,
- Unsteady aerodynamics and active flow control, and
- Intelligent autonomous air vehicles.

The 6.2 supporting technology program area is concerned only with

- Unsteady aerodynamics, and
- Unmanned combat air vehicles.

The total funding devoted to these program components is about $6 million per year. Given the complexity of the subjects addressed, ONR, of necessity, must develop a focused effort if it is to have any significant impact.

Comments on ASWT 6.1 and 6.2 Program Components

Shock-induced Fluorine Chemistry (6.1)

The committee was presented with only a minimal description of the shock-induced fluorine chemistry program component. The work is being done in support of the reactive material advanced technology demonstration (ATD) program and is being performed at the Naval Research Laboratory, Naval Air Warfare Center, Naval Surface Warfare Center, and Los Alamos National Laboratory. All evidence indicates that this program component is productive.

Unsteady Aerodynamics (6.1 and 6.2)

The unsteady aerodynamics program components grew out of a practical problem that arose during F-18E/F flight testing. When the F-18E/F is flying at a certain lift coefficient, whether in a turn or in level flight, one wing or the other tends to drop in an unpredictable, capricious fashion.[5] If the underlying phenomenon is truly aperiodic, the Navier-Stokes code may require a large number of repeat runs to provide enough data to characterize the statistics. If this is the case, the investigators may have

[5]The lift coefficient at which this event takes place, if it takes place at all, corresponds to a point where there is a slight reduction in the slope of the lift coefficient curve as a function of the angle of attack. For many airfoils, a gentle reduction in the slope of the lift coefficient curve as a function of the angle of attack is related to the aerodynamic interference between the flow near the airfoil's trailing edge and its wake. In the case of the F-18E/F, the aircraft motion seems at times to be preceded by or accompanied by a slight buffet.

difficulty in deciding when the solution has converged and when the fluctuations are in fact related to the phenomenon in question and are not just a by-product of the modeling. To complicate matters, other aerodynamic interference may play a role in the onset of this phenomenon. Although an explanation of the details of this phenomenon may be difficult to unravel, the committee believes that this is a potentially valuable research effort. On the other hand, it was not clear to the committee that the work presented that was related to active control of low-Reynolds-number flows has much future application to problems generic to naval forces.

Intelligent Autonomous Air Vehicles (6.1) and Uninhabited Combat Air Vehicles (6.2)

The 6.1 research work on intelligent autonomous air vehicle systems appears to be directed toward fundamental aspects of a networked command-and-control system for UCAVs, which is being further explored and demonstrated in various aspects in the ASWT UCAV 6.2 program component. Regarding UCAVs, the committee notes that there are several other important issues besides data links and control—e.g., sensors, payload, endurance on station, and aerodynamics (recovery and airborne agility)—and that there are major programs in the UCAV area funded by DARPA and the U.S. Air Force.

Considering the interest in and work on UCAVs in industry, and developments supported by the major U.S. Air Force and DARPA programs, ONR's 6.1 and 6.2 work in intelligent vehicles and UCAVs should focus on areas not included in the efforts of these other organizations or services.

While the ASWT 6.1 intelligent autonomous air vehicles research program component addresses several appropriate areas, the effort overall does not seem to be at the forefront of science.

The 6.1 work on intelligent autonomous air vehicle systems appears to duplicate past achievements (e.g., sequential estimation, Bayesian belief networks, optimal sensor selection, and nonlinear inverse dynamic control with exogenous disturbances). The committee is concerned with how "basic" this research really is. While the cadre of principal investigators is impressive, they do not appear to be working toward cohesive goals for the ASWT program.

The ASWT 6.1 and 6.2 supporting S&T should contain elements dedicated to other weapons areas requiring support at the fundamental level, such as described in several places above, e.g., GPS alternatives, guidance and control missile aerodynamics, and sensor backgrounds in the littoral.

Conclusions

The committee concludes that restructuring of the ASWT 6.1 and 6.2 supporting S&T program is needed.

- The number of projects in the intelligent air vehicles and UCAV areas is excessive.
- The scientific merit of some parts of the 6.1 intelligent air vehicles program is questionable.
- The 6.1 and 6.2 supporting S&T program should be restructured to assist other weapons areas needing fundamental support.

Recommendations

ASWT Supporting Science and Technology (S&T) (6.1 and 6.2) Program Areas. Reduce the number of intelligent air vehicles and UCAV projects, and then redirect 6.1 and 6.2 program components toward closer coupling to other important needs of ONR's ASWT program. Surviving 6.1 candidate program components also should be scrutinized carefully for scientific merit.

Appendixes

A

Committee Biographies

Alan Berman (Co-Chair), private consultant, currently consults for the Applied Research Laboratory of Pennsylvania State University (ARL/PSU), where he provides general management support and program appraisal. He also consults for the Center for Naval Analyses, where he assists with analyses of Navy R&D investment programs, space operation capabilities, and information operations. Dr. Berman has an extensive background in defense research and technology, particularly in regard to advanced weapon and combat systems. He is regarded as a leading expert on combat systems. His previous positions include dean of the Rosenstiel School of Marine and Atmospheric Sciences at the University of Miami and director of research at the Naval Research Laboratory. Dr. Berman has served on numerous government advisory and scientific boards. He is currently a member of the Naval Studies Board (NSB) and is serving on the National Research Council's (NRC's) Committee on Network-Centric Naval Forces. He is also a member of the Free Electron Laser (FEL) oversight board that advises the Jefferson National Laboratory of the Department of Energy on its FEL program.

George S. Sebestyen (Co-Chair) is chief executive officer and general manager of Systems Development, LLC. Dr. Sebestyen has an extensive background in defense tactical systems and is a leading authority on weapons and weapons issues. Prior to joining Systems Development, Dr. Sebestyen was president and CEO of CTA Space Systems, which was recently purchased by Orbital Sciences Corporation. At CTA, Dr. Sebestyen led numerous company efforts in areas of airborne avionics and command, control, and communications, as well as the development of exotic air and space platforms. Dr. Sebestyen's professional experience includes over 40 years in both military aircraft guidance and weapons systems. He has held senior positions at Boeing Aerospace Company, Sanders Associates, Litton Industries, and Melpar. In addition, Dr. Sebestyen once served as the assistant director for Tactical Systems Plans and Analysis for the Office of the Secretary of Defense. He has served on numerous government advisory and scientific boards. He recently served as vice chair for the Panel on Weapons as part of the NRC's Technology for Future Naval Forces study.

Eugene E. Covert is the T. Wilson Professor of Aeronautics, Emeritus at the Massachusetts Institute of Technology (MIT). Dr. Covert, a member of the National Academy of Engineering (NAE), has an extensive background in aerodynamics, aeronautics, gas dynamics, and solid and air-breathing propulsion. He has been employed at MIT since 1952 and has held numerous positions, including department head of Aeronautics and Astronautics. Dr. Covert has also served while on sabbatical as the U.S. Air Force chief scientist. Dr. Covert has served on numerous government advisory and scientific boards, including the Defense Science Board, U.S. Air Force Scientific Advisory Board, and NASA Aeronautics Advisory Committee. In addition, he is former member of the NRC's Aeronautics and Space Engineering Board (ASEB) and served on ASEB's Panel on Propulsion.

Jose B. Cruz, Jr., is the Howard D. Winbigler Chair in Engineering and professor of electrical engineering at Ohio State University (OSU). In addition to his teaching and research duties, Dr. Cruz serves as dean of the College of Engineering. Dr. Cruz, a member of the NAE, has an extensive background in guidance and control, particularly in regard to flight mechanics and aerospace electronic systems. Prior to joining OSU, he served as department chair for the Electrical and Computer Engineering Department at the University of California, Irvine. Dr. Cruz has held a number of teaching positions throughout his professional career, including positions at the Massachusetts Institute of Technology and the University of Illinois. His research interests include modeling and control of systems with multiple decision makers, as well as decentralized control of large-scale systems. Dr. Cruz is a member of the Institute of Electrical and Electronics Engineers. In addition, he has participated on numerous NRC studies, including most recently on the NIST Panel for the Manufacturing Engineering Laboratory.

Victor C.D. Dawson recently retired as an analyst at the Center for Naval Analyses (CNA). Dr. Dawson has an extensive background in naval gun systems and launchers, particularly as they apply to submarine and antisubmarine warfare issues. At CNA, Dr. Dawson has directed numerous studies on naval gun and surface ship torpedo defense, as well as conventional strike warfare and future carrier studies. Dr. Dawson is a former professor of mechanical engineering at the University of Maryland, where he taught courses in materials science, dynamics, and mechanical vibrations. Dr. Dawson is a fellow of the American Society of Mechanical Engineers. He recently served on the Panel on Weapons as part of the NRC's Technology for Future Naval Forces study.

Roger E. Fisher is director for DOD Programs at Lawrence Livermore National Laboratory (LLNL). In this capacity, Dr. Fisher coordinates market analyses and program development plans while at the same time enhancing LLNL's ability to support the DOD and ensure that the Laboratory is effectively trying to meet national security needs. Dr. Fisher has an extensive background in advanced weapon and strike systems, particularly in regard to maneuverability and penetration issues. From 1994 to 1996, Dr. Fisher served as deputy assistant secretary for Research and Development, in the Office of the Assistant Secretary for Defense Programs, Department of Energy (DOE). Prior to joining DOE, he was assigned to the Office of the Secretary of Defense where he managed the DOD strategy for improving precision strike warfare. Dr. Fisher has held numerous senior government positions throughout his 30-plus-year career, including science advisor for the U.S. Third Fleet and advanced technical advisor for the Chief of Naval Operations. Dr. Fisher's interests include aerodynamics, and he is a Federal Aviation Agency (FAA)-certified commercial pilot.

Eliezer G. Gai is vice president of engineering at the Charles Stark Draper Laboratory. Dr. Gai has an extensive background in tactical systems. He joined Draper in 1975 as a staff engineer, where his work focused on control and flight dynamics. Today, Dr. Gai is heavily engaged in the development of micromechanical systems, particularly in regard to their application in munitions guidance, missile guidance, and theater missile defense technologies. Prior to joining Draper, he was a research assistant for the Department of Aeronautics at the Massachusetts Institute of Technology. Dr. Gai is a fellow of

the American Institute of Aeronautics and Astronautics and recently served as a member of the Defense Science Board's Task Force on Joint Superiority for the 21st Century.

Daniel N. Held is director and chief scientist for Systems Technology and Systems Development at Northrop Grumman Corporation. Dr. Held has a background in guidance and control, particularly in regard to electronic sensors. He is the author of over 50 technical papers and has received numerous awards for his work involving sensor systems technology. The majority of his accomplishments over the last 20 years have focused on advancing concepts and applications for synthetic aperture radar. Prior to joining Grumman, Dr. Held served as vice president of Research, Development, and Advanced Systems at Westinghouse's Norden Systems Division where he was primarily responsible for solving many of the critical issues associated with the Multi-Mode Radar System. He also once served as deputy project manager at the NASA/CalTech Jet Propulsion Laboratory. Dr. Held has served on numerous government advisory and scientific boards. He recently chaired the Naval Research Advisory Committee on GPS Vulnerability.

Bernard H. Paiewonsky is an adjunct research staff member in the Science and Technology Division at the Institute for Defense Analyses (IDA). Dr. Paiewonsky has an extensive background in aerospace technology, flight dynamics, aircraft and spacecraft design, and hypersonics spacecraft propulsion. Prior to joining IDA, Dr. Paiewonsky served as deputy for technology in the Office of the Assistant Secretary of the U.S. Air Force for Acquisition. Dr. Paiewonsky's professional experience also includes assignments in the Department of Justice and the Executive Office of the President. In addition, he served as head of flight mechanics for Aeronautical Research Associates of Princeton, Incorporated. Dr. Paiewonsky has research interests ranging from national security issues to optimization theory and application. He has served on numerous scientific committees and advisory boards and was an associate editor of the *American Institute of Aeronautics and Astronautics Journal* and the *Journal of Spacecraft and Rockets.*

Robert F. Stengel is a professor of mechanical and aerospace engineering and director of the Laboratory for Control and Automation at Princeton University. Dr. Stengel's background is in advanced air vehicles. His current research focuses on failure-tolerant and robust control, neural networks, and air traffic control, all of which are supported by the FAA and NASA. While at Princeton, Dr. Stengel was director of the Flight Research Laboratory, where he conducted pioneering experimental research on digital flight control systems, flight computer networking via fiber optics, aircraft flying qualities, and aerodynamic system identification. This research used Princeton's two fly-by-wire, variable-stability aircraft and a specially instrumented sail plane. Prior to his coming to Princeton, Dr. Stengel worked at the Analytic Sciences Corporation, Charles Stark Draper Laboratory, the U.S. Air Force, and NASA. He has served on numerous government advisory and scientific boards. He recently served on the NRC's Mobility Systems Panel for the Board on Army Science and Technology.

John F. Walter is program area manager for the Strike Warfare Program Office of the Power Projection Systems Department at Johns Hopkins University Applied Physics Laboratory (JHU/APL). Dr. Walter has a background in the development of precision strike weapons and associated support systems. While at JHU/APL, he also previously held positions as project manager for the Tomahawk Land-Attack Project and technical area manager for autonomous flight control systems for the harpoon missile. Dr. Walter's research interests include laser physics, laser propagation in the atmosphere, electro-optics, inertial navigation, and missile guidance. He is a member of the American Institute of Aeronautics and Astronautics and of the Precision Strike Association Board of Directors.

Jay B. Yakeley, a retired rear admiral, U.S. Navy, is a private consultant. Admiral Yakeley has an extensive background in naval operational and management issues. Admiral Yakeley's last duty assignment was director, Programming Division for the Deputy Chief of Naval Operations (Resources, War-

fare Requirements, and Assessments). Today, Admiral Yakeley is a consultant to the Johns Hopkins University Applied Physics Laboratory, where he is engaged in precision strike and power projection warfare activities.

B

Acronyms and Abbreviations

ACTD	Advanced concept technology demonstration
ASWT	Air and Surface Weapons Technology (program)
ATD	Advanced technology demonstration
ATR	Automatic target recognition
AWACS	Airborne warning and control system
BOV	Board of Visitors
C^2	Command and control
C^3I	Command, control, communication, and intelligence
CEP	Circular error probable
DARPA	Defense Advanced Research Projects Agency
ELINT	Electronic intelligence
ERGM	Extended-range guided missile
GOTChA	Goals, objectives, technical challenges, and approaches
GPS	Global Positioning System
HARM	High-speed antiradiation missile
IMU	Inertial measurement unit
INS	Inertial navigation system

IR	Infrared
IR&D	Independent research and development
JDAM	Joint direct-attack munition
JSOW	Joint standoff weapon
LADAR	Laser detecting and ranging
MEMS	Microelectromechanical system
MTI	Moving target indicator
NAWC	Naval Air Warfare Center
NRC	National Research Council
NSWC	Naval Surface Warfare Center
ONR	Office of Naval Research
P^3I	Preplanned product improvement
PEO	Program executive office
R&D	Research and development
RAM	Rolling airframe missile
RDT&E	Research, development, testing, and evaluation
RF	Radio frequency
S&T	Science and technology
SEAD	Suppression of enemy air defense
SFW	Sensor-fused weapon
SLAM (ER)	Standoff land-attack missile, extended range
TOF	Time of flight
TOPART	Tomahawk-Predator advanced relative targeting
UAV	Uninhabited air vehicle
UCAV	Uninhabited combat air vehicle